

CP violating effects in the decay $Z \rightarrow \mu^+ \mu^- \gamma$ induced by $ZZ\gamma$ and $Z\gamma\gamma$ couplings

M. A. Pérez* and F. Ramírez-Zavaleta†

Departamento de Física, CINVESTAV, Apartado Postal 14-740, 07000, México, D. F., México

(Dated: February 2, 2008)

We analyze possible CP-violating effects induced in the Z decay with hard photon radiation by γZZ and $\gamma\gamma Z$ anomalous vertices. We estimate the sensibility of future linear collider experiments on these couplings coming from CP-odd asymmetries associated to angular correlations of the three particle final state in $e^+e^- \rightarrow Z \rightarrow \mu^+ \mu^- \gamma$. We find that a linear collider with an integrated luminosity of 500 fb^{-1} and $\sqrt{s} = 0.05 \text{ TeV}$ can place the bound $|h_1^{\gamma, Z}| < 0.92$ at the 90% confidence level for these couplings.

PACS numbers: 14.70.Pw, 13.38.Dg

Trilinear gauge boson self-couplings have been studied as a new source of CP-violating interactions at high energies [1, 2, 3, 4]. In particular, anomalous neutral triple gauge couplings (NTGC), which are not present at tree level in the Standard Model (SM), may induce CP-violating effects in processes such as $\gamma e \rightarrow Ze$ [5], $e^+e^- \rightarrow \gamma Z$ [6], $e^+e^- \rightarrow ZZ$ [7], $\gamma\gamma \rightarrow t\bar{t}$ [8] and $p\bar{p} \rightarrow Z\gamma$ [4].

In the present paper we are interested in studying the CP-violating effects induced by NTGC in the radiative decay $Z \rightarrow \mu^+ \mu^- \gamma$. The contributing diagrams to this decay mode are depicted in Fig. 1. Fig. 1(a) refers to the SM contribution, the other diagrams include CP-violating effective vertices denoted by heavy dots. To lowest order, the CP-violating effects in this reaction are induced by the interference between the SM contribution and any one of the other diagrams shown in Fig. 1. Figs. 1(b) and 1(c) correspond to the contributions arising from the electric and weak dipole moments of the muon. Since these moments are tightly bounded [9], their contribution exclude any observable CP-violating effect in the decay $Z \rightarrow \mu^+ \mu^- \gamma$ [4, 10]. The possible CP-violating effects induced by the contact interaction $\mu\mu\gamma Z$ shown in fig. 1(d) have been studied in Ref. [10]. However, it has been pointed out [4, 11] that a fully gauge invariant effective Lagrangian that induces this local interaction also generates the CP-violating vertices $\mu\mu Z$ and $\mu\mu\gamma$ shown in Fig. 1(b) and 1(c). When all these new vertices are taken into account, the interference between the lowest order SM diagram and the new CP-violating contributions vanishes for the process $e^+e^- \rightarrow \mu^+ \mu^- \gamma$ and one is left with no CP-odd effects. Nonetheless, the L3 collaboration searched for CP-violating effects in the decay of the Z boson with hard photon radiation and they could set an upper bound on the CP-violating coupling $\mu^+ \mu^- \gamma Z$ [12].

We will assume that possible CP-violating effects in the decay $Z \rightarrow \mu^+ \mu^- \gamma$ are induced by the effective vertices $ZZ\gamma$ and $Z\gamma\gamma$ shown in Fig. 1(e). In Ref. [10], it was argued that is not necessary to study the CP-violating effects induced in this decay mode by the NTGC since the Lorentz structure of the respective amplitude reduces to that obtained for the contact interaction $\mu^+ \mu^- \gamma Z$, Fig. 1(d). Our point of view in the present paper is that this argument is not enough to disregard the contribution of the NTGC to the CP-violating effects in the decay $Z \rightarrow \mu^+ \mu^- \gamma$. It has been pointed out [3, 13] that these effective vertices have a rather rich structure in the framework of the effective Lagrangian formalism. They may be generated in both the linear and non-linear realization of the $SU(2)_L \times U(1)$ gauge symmetry. We have shown [3] that in both realizations, the NTGC induce the same Lorentz structure but that this structure may be induced by operators of dimension 6 in the non-linear scenario or operators of dimension 8 in the case of the linear realization of the $SU(2)_L \times U(1)$ symmetry. As a consequence, any one of these constructions may generate CP-odd observables which could be independent of those induced by the $\mu^+ \mu^- \gamma Z$ contact interaction or the weak and electric dipole moments of the muon.

The most general form of the $Z^\alpha(p)V^\beta(q)\gamma^\mu(k)$ vertex function, with $V^\beta = \gamma, Z$, when Z^α and γ^μ are on-shell and which respects Lorentz and electromagnetic gauge invariance is given by [2, 3]

$$\begin{aligned} \Gamma_{\alpha\beta\mu}^{ZV^*\gamma}(p, q, k) = & \frac{ie}{m_Z^2} [h_1^V(k^\alpha g^{\mu\beta} - k^\beta g^{\mu\alpha}) + \frac{h_2^V}{m_Z^2} q^\alpha (q \cdot k g^{\beta\mu} - k^\beta q^\mu) \\ & + h_3^V \epsilon^{\alpha\beta\mu\nu} k_\nu + \frac{h_4^V}{m_Z^2} q^\alpha \epsilon^{\beta\mu\nu\rho} p_\nu q_\rho] (q_V^2 - m_V^2), \end{aligned} \quad (1)$$

where m_Z is the Z -boson mass and the first two terms in (1) are CP-violating and the other two are CP-conserving. The

*E-mail: mperez@fis.cinvestav.mx

†E-mail: rzf@fis.cinvestav.mx

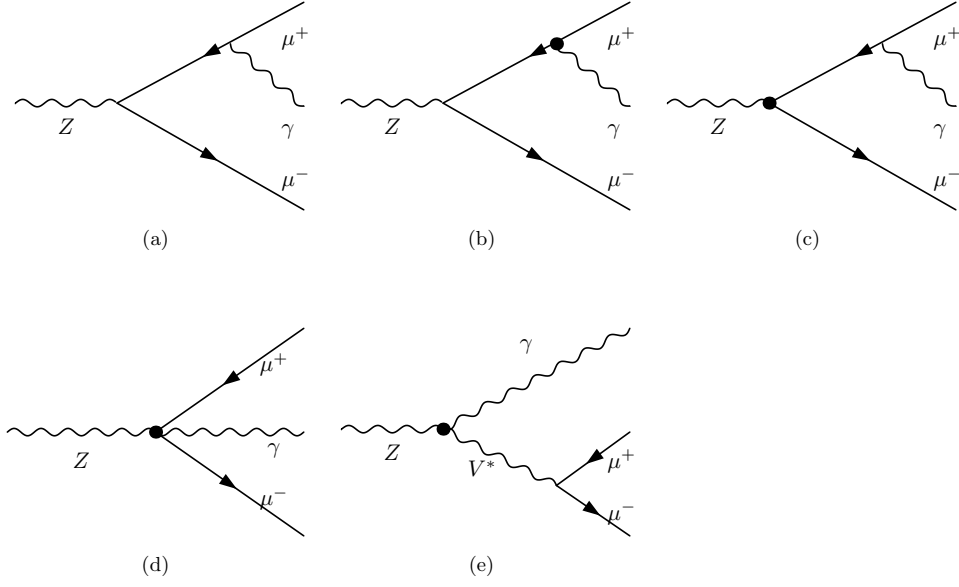


FIG. 1: Feynman diagrams contributing to CP-violating effects in the decay $Z \rightarrow \mu^+ \mu^- \gamma$. The heavy dots denote CP-violating effective vertices. Crossed diagrams are not shown, V^* stands for Z or γ .

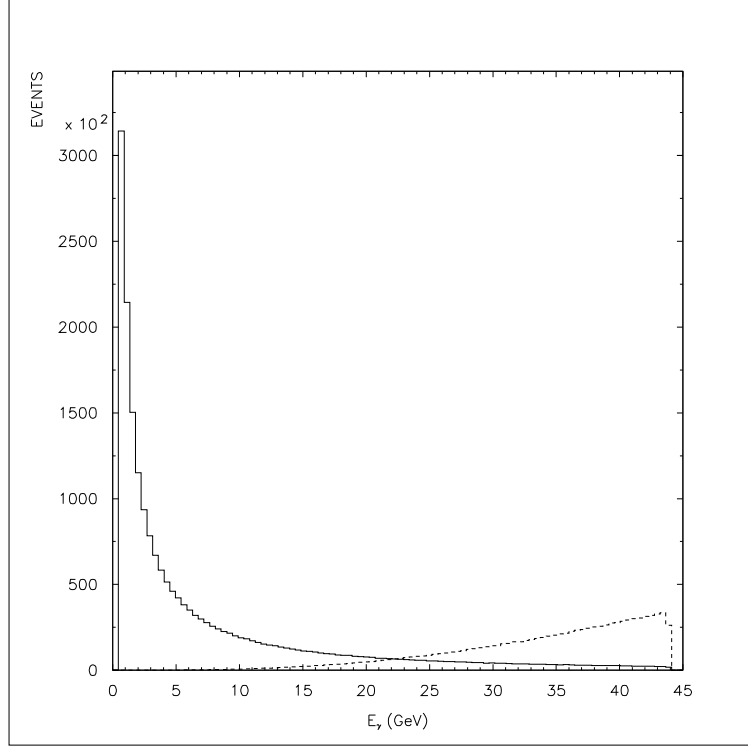


FIG. 2: Energy distributions of the photon emitted in $e^+e^- \rightarrow \mu^+\mu^-Z$ for SM (solid line) and TNGB (dotted line) contributions with $h_1^V = 1$.

respective couplings $h_i^{\gamma,Z}$ have been bounded in e^+e^- and $p\bar{p}$ collisions [9, 14]: $h_1^Z \in [-0.15, 0.14]$, $h_2^Z \in [-0.09, 0.08]$, $h_3^Z \in [-0.22, 0.11]$, $h_4^Z \in [-0.07, 0.15]$, $h_1^\gamma \in [-0.06, 0.06]$, $h_2^\gamma \in [-0.05, 0.02]$, $h_3^\gamma \in [-0.06, 0.004]$, $h_4^\gamma \in [-0.004, 0.042]$.

Following Ref. [10, 12], we will use the angular correlations of the three particles in the final state in $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^- \gamma$ in order to test CP-violating effects induced by the anomalous $ZZ\gamma/Z\gamma\gamma$ couplings. The following CP-odd

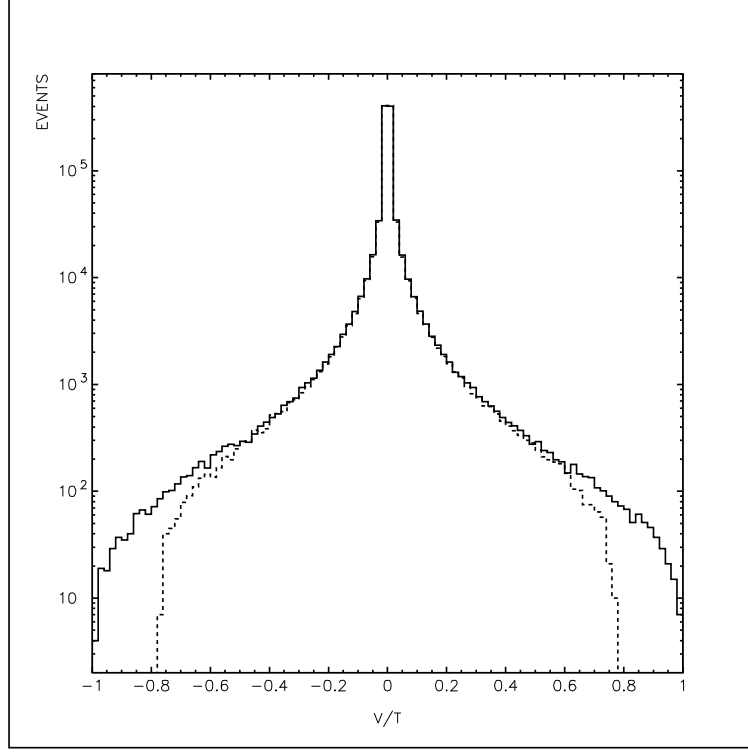


FIG. 3: Distributions for the CP-odd observables V (solid line) and T (dotted line) corresponding to the interference between the SM and TNGB contributions ($h_1^V = 1$).

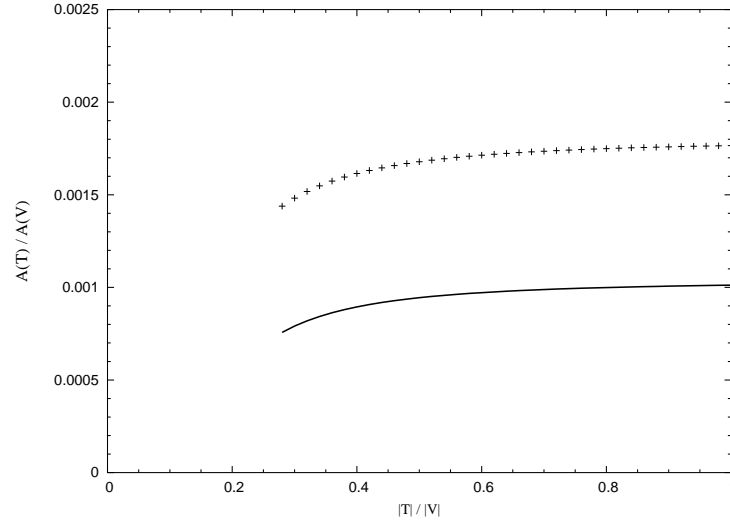


FIG. 4: Asymmetries for the CP-odd observables V (dotted line) and T (solid line) corresponding to the interference between the SM and TNGB contributions ($h_1^V = 1$).

observables have been proposed [10] to search for CP-violation in this radiative decay

$$\begin{aligned} T &= (\hat{\mathbf{k}}_{\mu^+} - \hat{\mathbf{k}}_{\mu^-}) \cdot \hat{\mathbf{p}}_{e^+} (\hat{\mathbf{k}}_{\mu^+} \times \hat{\mathbf{k}}_{\mu^-}) \cdot \hat{\mathbf{p}}_{e^+} \\ V &= (\hat{\mathbf{k}}_{\mu^+} \times \hat{\mathbf{k}}_{\mu^-}) \cdot \hat{\mathbf{p}}_{e^+}. \end{aligned} \quad (2)$$

where $\hat{\mathbf{k}}_{\mu^+}$ and $\hat{\mathbf{k}}_{\mu^-}$ are both the unitary vectors of muon and antimuon, respectively, $\hat{\mathbf{p}}_{e^+}$ is the direction of colliding positron.

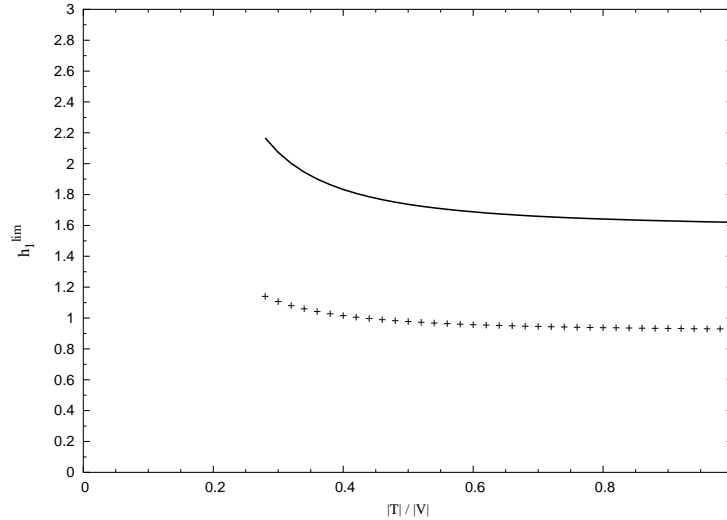


FIG. 5: The 90% C. L. contours on h_1^V from the asymmetries A_T (solid line) and A_V (dotted line) as function of the CP-odd variables T and V .

We use the narrow-width approximation and in order to suppress the SM contributions from radiative Z decay, we impose the cuts: $P_{T\gamma} \geq 10$ GeV, $P_{T\mu^-} \geq 20$ GeV, $P_{T\mu^+} \geq 20$ GeV [4, 12]. In Fig. 2 we present the energy distributions for the emitted photon when we consider separately the SM and TNGB contributions. While the SM contribution is peaked in the forward direction, the CP-odd distribution has a maximum at large values of the photon energy. Fig. 3 shows the distributions expected in this Z radiative decay for the observables T and V obtained with a Monte Carlo program for the numerical integration using h_1^V . It is observed a rather slight asymmetry between negative and positive values of T and V . In order to estimate the sensitivity of the TESLA collider to the h_1^V couplings, we will make use of the relative asymmetries between negative and positive values of the observables T and V [12]:

$$A_T = \frac{N_{T>0} - N_{T<0}}{N_{T>0} + N_{T<0}} \quad (3)$$

$$A_V = \frac{N_{V>0} - N_{V<0}}{N_{V>0} + N_{V<0}}. \quad (4)$$

In Fig. 4 these asymmetries are shown for intervals in $|T|$ and $|V|$, respectively. Using these results, we can obtain 90 % CL limits on the h_1^V vertices as a function of $|T|$ and $|V|$ (Fig. 5). We find that the best limits are obtained for $|V| \sim 1$, which correspond to $|h_1^V| \leq 0.92$. These limits correspond to a future linear collider with $\sqrt{s} = 500$ GeV and an integrated luminosity of 500 fb^{-1} . We found no difference for the asymmetries induced by the h_1^Z and h_1^γ couplings due to the Lorentz structure shown in Eq. (1), while the respective CP-odd effects induced by the couplings h_2^V are even more suppressed due to the extra suppression factor m_Z^2 in Eq. (1).

In conclusion, our numerical study has shown that anomalous CP-violating vertices $ZZ\gamma$ and $Z\gamma\gamma$ also give rise to CP-odd asymmetries associated to angular correlations of the three particle final state. While rare Z decays may be sensitive to both the CP-conserving and CP-violating h_i^V couplings [16], the detection of the A_T and A_V asymmetries in the radiative decay $Z \rightarrow \mu^+\mu^- \gamma$ may be used to get specific constraints on the CP-violating h_i^V couplings. We have derived sensitivity limits expected in a future linear collider for the CP-violating vertices $ZZ\gamma$ and $Z\gamma\gamma$. These sensitivity limits on h_1^V are about one order of magnitude below than those obtained from CP-conserving observables in e^+e^- experiments [14, 15] or from future experiments in $e^+e^- \rightarrow \gamma Z$ with a transverse beam polarization [7]. However, the analysis presented in this paper has shown that an improvement in the luminosity expected in a future TeV linear collider [17] may impose better and independent bounds on the CP-odd couplings h_1^V .

The calculations involved in the present work needed a considerable symbolic and numerical computation. We achieved this objective by using FeynCalc into the Mathematica for symbolic manipulations as reduction of traces of Dirac matrices, simplification of large expressions, etc. Fortran program code was used as translator from results obtained by VEGAS to graphical environment by program PAW++. The numerical phase space integrations were done with VEGAS program into the COMPHEP, like also Monte Carlo events generation.

Acknowledgments

We acknowledge support from Conacyt and SNI (México). We would like to thank G. Tavares-Velasco for collaboration in the early stages of the present work and H. Castilla and A. Sánchez for useful discussions.

-
- [1] W. J. Marciano, A. Queijeiro, Phys. Rev. **D33** (1986) 3449.
 - [2] K. Hagiwara, R. Peccei, D. Zeppenfeld, Nucl. Phys. **B282** (1987) 253.
 - [3] F. Larios, M. A. Perez, G. Tavares-Velasco, J. J. Toscano, Phys. Rev. **D63** (2001) 113014.
 - [4] S. Dawson, G. Valencia, Phys. Rev. **D52** (1995) 2717; S. Dawson, Xiao-Gang He and G. Valencia, Phys. Lett. **B390** (1997) 431.
 - [5] S. Y. Choi, Z. Phys. **C68** (1995) 163; T. G. Rizzo, Phys. Rev. **D54** (1996) 3057; S. Atag, I. Sahin, Phys. Rev. **D68** (2003) 093014.
 - [6] D. Choudhury and S. D. Rindani, Phys. Lett. **B335** (1994) 198; K. J. Abraham and B. Lampe, Phys. Lett. **B446** (1999) 163; B. Ananthanarayan *et al.*, Phys. Lett. **B593** (2004) 95.
 - [7] D. Chang, W. Y. Keung, P. B. Bal, Phys. Rev. **D51** (1995) 1326; J. Biebel, Phys. Lett. **B448** (1999) 125.
 - [8] P. Poulose, S. D. Rindani, Phys. Lett. **B452** (1999) 347.
 - [9] Particle Data Group, Phys. Lett. **B592** (2004) 1.
 - [10] W. Bernreuther, U. Low, J. P. Ma, O. Nachtmann, Z. Phys. **C43** (1989) 117; W. Bernreuther, A. Brandenburg, P. Haberl, O. Nachtmann, Phys. Lett. **B387** (1996) 188; D. β ru β , O. Nachtmann, P. Overmann, Eur. Phys. J. **C2** (1998) 191.
 - [11] M. Traseira, F. J. Vegas, Phys. Lett. **B262** (1991) 120.
 - [12] M. Acciarri *et al.*, L3 Collaboration, Phys. Lett. **B436** (1998) 428.
 - [13] J. Alcaraz, Phys. Rev. **D65** (2002) 075020; G. J. Gounaris, J. Layssac y F. M. Renard, Phys. Rev. **D62** (2000) 073013; D. Choudhury *et al.*, Int. J. Mod. Phys. **A16** (2001) 4891.
 - [14] St. Wynhoff, Proceedings of ICHEP 2002, pp. 198-201; P. Achard *et al.*, L3 Collaboration, Phys. Lett. **B597** (2004) 119.
 - [15] S. Atag and I. Sahin, Phys. Rev. **D70** (2004) 053014.
 - [16] M. A. Perez, G. Tavares-Velasco, J. J. Toscano, Int. J. Mod. Phys. **A19** (2004) 159.
 - [17] J. Ellis, arXiv: **hep-ph/0409140**.